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Ask, don't tell

van Vondel, Sabine; Steenbeek, Henderien; van Dijk, Marijn; van Geert, Paul

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Abstract (98 words)

Studying real-time teacher-student interaction provides insight into student's learning processes. First, we examined the effect of the Video Feedback Coaching intervention by focusing on changes in teacher-student interaction patterns. In this study, upper grade elementary teachers were supported to optimize their instructional skills required for co-constructing scientific understanding. Second, the underlying dynamics of those changes were examined by illustrating an in-depth micro-level analysis of teacher-student interactions. The intervention condition showed significant changes in the way scientific understanding was co-constructed. Results provided insight into how teacher-student interaction can elicit optimal co-construction and how this process changes during an intervention.

Keywords: Complex dynamic systems approach, Co-construction, Scientific understanding, Teaching Intervention, State Space Grid

The importance of science and technology lessons in elementary education is widely acknowledged (Appleton, 2003; Jorde & Dillon, 2012; National Research Council, 2011). The rapid changes in 21st century's society make considerable demands on human skills and adaptability. In order to be able to meet these requirements, children should be prepared to become active agents of their own learning process from an early age on (Schraw, Crippen, & Hartley, 2006; Authors, 2011 [details removed for peer review]). Inquiry-based learning provides opportunities to engage students in scientific processes and invite them to use critical thinking skills as they search for answers (Gibson & Chase, 2002). Several scholars emphasize that instructional quality of teachers is crucial for students' cognitive gains (Baumert et al, 2010; Oliveira, 2010). However, at present we still know relatively little about the underlying micro-level dynamics responsible for change in students' scientific understanding (Zimmerman, 2007). Put differently, the micro-level processes are called for to enhance our understanding of learning during science and technology education.

In this study, a complex dynamic systems approach is used as a framework for studying these micro-level processes. We focus on the effectiveness of an educational intervention based on video feedback coaching (Author et al., 2016a [details removed for peer review]), which aims to improve science and technology education in the upper grades of elementary education, i.e., for 10 to 12-year-old students. The complex dynamic systems approach views learning as a nonlinear process that emerges in person-in-context interactions over time (Fischer & Bidell, 2006; Author, 2003 [details removed for peer review]). In other words, the competence of a student is unfolding in the individual while simultaneously modifying and being modified by the changing behavior of the teacher (Fogel, 2009; Authors, 2013a [details removed for peer review]). Increased scientific understanding, as displayed in teacher-student interaction, emerges and stabilizes over several lessons (Authors, 2013a). The goal of the present study is first, to gain insight into how teacher and students co-construct scientific understanding, and second, how this process of co-construction develops during the Video Feedback Coaching program.

1.1 Co-construction of scientific understanding

Scientific understanding can be defined as conceptual knowledge related to the underlying principles of scientific phenomena (Zimmerman, 2007). Several studies show that students often do not spontaneously display scientific understanding (Chin & Brown, 2002; Engel, 2006, 2009). Gains in students' scientific understanding can be measured by focusing on the explanations and predictions they use (Henrichs & Leseman, 2014; Treagust & Tsui, 2014). Gains emerge in actual activities and verbal utterances of students while performing an experiment¹. Hence, it is important for teachers to stimulate students' active participation, to spark students' curiosity and to elicit students' thinking processes (Treagust & Tsui, 2014). Inquiry-based learning situations are ways to do so. The objective of inquiry-based learning is to move towards the construction of scientific understanding in context and thus to move away from the recollection of facts (Cuevas, Lee, Hart, & Deaktor, 2005; National Research Council, 2011). Teachers can use various instructional skills as means to make their classroom interaction more thought-provoking with the aim of cognitively activating students (Baumert et al., 2010) and achieving deeper scientific understanding in their students (Author et al., 2016a). Examples of such instructional skills, used while students are engaged in inquiry learning (Gibson & Chase, 2002), are thought-provoking questioning (Oliveira, 2010) or encouraging (Authors, 2013b). This understanding of scientific concepts takes place as a co-construction process in a specific dynamic context (Sorsana, 2008). One of the major features of such a process is that teachers and students need to constantly adapt to each other's contribution during real-time interaction. That is, co-construction refers to the process of reciprocal influence (Thelen & Smith, 1994; Author, 1994 [details removed for peer review]), which in the case of classroom practices mainly concerns the behavior of a student that influences the reaction of a teacher and vice versa (figure 1). Co-construction is about constructing insights, understanding and explanations in real-time, i.e., about constructing more complex and more adequate scientific descriptions and explanations in a collaborative process. This is reflected in active participation of both teacher and student.

¹ In this study the focus is on verbal utterances, as a representative of the interaction. We acknowledge that the interaction is much more complex than only the verbal aspect, but it is beyond the scope of this article to focus on non-verbal aspects as well.

< Figure 1 about here >

1.2 Teacher-student interaction

When it comes to instructional practice, there is no-one-size-fits-all-students approach (Granott, 2005; Van de Pol, Volman, & Beishuizen, 2010). However, certain patterns of interaction can hinder active construction of understanding, while others favor it (Ge & Land, 2003; Granott, 2005; Authors, 2012b [details removed for peer review]). The extent and quality of stimulation incorporated in teachers' reactions to student utterances can be seen as a key characteristic of educational quality (Baumert et al., 2010). Stimulation is, in the present study, defined as the extent to which teachers use verbal actions that support students in displaying (higher-order) scientific understanding. A typical format of teacher-student interaction is a three-part exchange structure consisting of initiation, student response, and teacher evaluation (IRE) (Dillon, 1988; Lemke, 1990). Often this interaction pattern takes the form of teacher directed interaction, in that the teacher initiates with a closed question, that requires a predetermined short answer, and that is usually focused at recall (Chin, 2006). The teacher then praises correct answers or corrects those that are wrong. The dialogue inherent to this style mainly consists of asking closed question, providing information and giving instruction. Hence, students are discouraged from being active agents in their own learning process (Ryan & Deci, 2000; Wehmeyer, Palmer, Agran, Mithaug, & Martin, 2000), as they are prevented from displaying reasoning skills (Topping & Trickey, 2007). In this study, this type of interaction is referred to as 'non-optimal' interaction, as the teacher's utterances do not evoke higher order thinking skills, i.e., are non-stimulating, and the student's role in the co-construction of meaning is thus minimized.

The objective of inquiry-based science lessons is, however, to facilitate the active construction of students understanding (National Research Council, 2011). This implies that teacher's reactions can be used as a means to guide and scaffold students thinking. When teachers employ a stimulating classroom interaction, students are invited to participate in co-constructing scientific understanding. Thought-provoking questions are questions that cause an increase in the frequency and length of students' answers reflecting higher order thinking skills (Chin, 2006; Oliveira, 2010). In this process

the teacher's encouragements are considered to be beneficial for an increase in the complexity of student utterances (Authors, 2013b). An increase in the amount and length of thought-provoking teacher-student interactions is important as these involve an increase in active construction of understanding (Topping & Trickey, 2014). The above-mentioned interaction pattern of IRE sequences can be transformed in a more productive action sequence by replacing the third move by a follow-up (IRF; Baumert et al., 2010; Chin, 2006; Lee & Kinzie, 2012; Wells, 1993). This follow-up, for instance a thought-provoking question, can be used as the starting point to deepen student's scientific understanding. This means that a new three-part exchange starts. In that case, the student's answer is followed by a stimulating follow-up of the teacher and the student in turn answers with an elaboration (IRFRFR). This type of interaction will in the remainder of this article be referred to as an 'optimal' interaction, as both the teacher and student's role in the co-construction of meaning is optimized. The process of co-construction can be seen as a sequence of such interaction patterns.

1.3 Recurrent interaction patterns

Instructional practice of the teacher, i.e., the way teachers respond to student utterances, is an aspect of classroom processes that can be manipulated by teachers; i.e., it is under their control. As teacher-student interaction is at the center of student learning (Vygotsky, 1986), it holds promise as a way to better engage students in co-constructing scientific understanding. However, teacher-student interaction patterns appear hard to change (Authors, 2012b). The complex dynamic systems approach explains these rigid, stable patterns as self-sustaining patterns, so called attractors. Attractors are states that have a much higher probability of recurrence compared to other states (Thelen, 1992; Author, 1994). Attractors are, in this study operationalized as, states that are not only visited for the longest duration (preferred states) but are also often visited, i.e., the student-teacher interaction often recurs towards that state. Often, external perturbations are necessary to change such recurrent interaction patterns and replace them by new, more adequate patterns (Author, 1994). An intervention can be seen as such a perturbation in an existing pattern of teacher-student interactions (Authors, 2016b). As an illustration, during science and technology activities a teacher may routinely initiate interactions by asking closed or knowledge-based questions. These non-stimulating sequences become a self-

sustaining comfortable ('preferred') state for both the teacher and students, because students respond with knowledge reproduction, which in turn, most likely, evoke more closed questions. This self-sustaining recurrent pattern can be perturbed by an intervention that directly stimulates teachers to change their timing and format of questions. If teachers begin to change their questioning strategies towards open-ended initiation and follow-up questions, students may at first show resistance. Students are not used to this form of questioning and are thus not inclined to give the kind of answers that the teacher might need to continue a high-quality style of questioning during the lesson. In other words, the reaction of students discourages the teacher to continue with this high-quality type of questioning. However, if the teacher persists in using these open-ended questions and the students start to engage in critical thinking, the teacher-student interaction might change permanently over time. Finally resulting in a new, more stimulating, attractor state, which in itself becomes a self-sustaining pattern of interaction. In the period between old and new attractor states, there is typically a phase of destabilization (Author, 2007 [details removed for peer review]). Increased variability is a typical indicator of destabilization. In the classroom this might be seen as temporal instability of the teacher-student interaction during which the system explores new ways of communication. As argued above, a change in interaction patterns demands new behaviors and responsibilities from students and teachers alike. Hence, the importance of focusing on dyadic measures is highlighted.

1.4 Depicting change and destabilization

Learning and change are inherently related. Change occurs from the real-time (micro level) timescale to the long-term developmental (macro level) timescale (Lewis, 2002; Smith & Thelen, 2003; Authors, 2005 [details removed for peer review]). The relation between these timescales is that the change at the real-time level influences the long-term development as well as that the long-term development affects the real-time processes, i.e., the timescales are nested (Lewis, 2002; Smith & Thelen, 2003; Authors, 2005). The experiences and processes of teacher and students (micro level) result in certain stable but complex interaction patterns (macro level) leading to specific learning outcomes, such as a certain level of scientific understanding. In the case of co-constructed scientific understanding as an outcome, the real-time behaviors (the utterances of a teacher and student in

interaction; micro level) are the building blocks of this longer term or global learning process (macro level; Hollenstein, 2013; Rappolt-Schlichtmann et al., 2007; Authors, 2014 [details removed for peer review]). At the same time, these more global patterns constrain the real-time learning and teaching behavior (Hollenstein & Lewis, 2006; Authors, 2012b; Authors, 2014). For instance, following the example described before of a lesson consisting of recurrent interactions in which the teacher poses closed questions, students respond with non-complex utterances and the teacher reacts with providing correct information or instructions. These micro-level processes result in a macro-level 'non-optimal' interaction pattern and vice versa. We define micro level as real-time behavior of the teacher and students during a single lesson and macro level as the relatively stable and predictable pattern of the way scientific understanding is co-constructed over the course of interaction patterns.

The students' level of scientific understanding and the extent to which teacher utterances are stimulating can be analyzed as coordinated processes. State space grid (SSG) analysis is a method for analyzing synchronized event sequences based on complexity principles (Hollenstein, 2013). The focus is on the joint states of the teacher and students. SSG can be used to depict both micro level (e.g., Pennings et al., 2014) and macro level changes in these interactions patterns (e.g., Hollenstein, 2013; Turner, Christensen, Kackar-Cam, Trucano, & Fulmer, 2014). By focusing on a single lesson, insight can be gained into how a system functions in real-time. For instance, moment-to-moment dynamic variability of the system behavior that varies because of reciprocal influence of both teacher and students can be studied. By focusing on a sequence of lessons in a particular class, insight can be gained into variations in macro-level processes that come from external perturbations, such as an intervention.

1.5 Video Feedback Coaching for teachers

One method that can be used to aid teachers in changing interactional practices is offering video feedback of own classroom behaviors (e.g., Mortenson & Witt, 1998). Video recordings of teacher's practice are used to foster professional reflection and improve instructional skills (Seidel, Stürmer, Blomberg, Koberg, & Schwindt, 2010). The objective of the Video Feedback Coaching for teachers (VFCt) was to improve the teacher's instructional skills (Wetzels, 2015). During the

intervention, teachers were encouraged and assisted to use thought-provoking questions and encouragements to guide the acting and thinking process of students (e.g., Chin, 2006; Oliveira, 2010) in order to scaffold students to higher levels of functioning (Authors, 2012b; Van de Pol, Volman, & Beishuizen, 2011). Such an instructional strategy was aimed to increase students' cognitive participation, and in doing so help them develop more and higher complexity levels of scientific understanding. In other words, teachers were encouraged to move towards 'optimal' interaction patterns to co-construct scientific understanding. The VFCt intervention contained the following evidence-based key elements: (1) improving teachers' knowledge about teaching science and scientific skills, (2) establishing behavioral change by improving teachers' instructional skills by means of (a) video feedback coaching and (b) articulating personal learning goals (see 5.1 appendix A; Author et al., 2016a).

1.6 Present study

In the present study, change in the co-construction of scientific understanding is examined by analyzing student-teacher interactions during science and technology lessons. On the one hand this paper examines the effect of the VFCt intervention by focusing on the macro level changes of student-teacher interaction patterns. On the other hand, we aim to examine the underlying dynamics of such changes by illustrating an in-depth micro-level analysis of recurrent student-teacher interactions. The first research question is about the initial state, i.e., the microstructure of interaction preceding the intervention. We will explore the characteristics of the process of co-construction of scientific understanding during regular science and technology lessons, that is before the intervention (RQ1). We address dyadic measures, i.e., the sequence and recurrence of students' level of scientific understanding corresponding with the simultaneous level of stimulation of the teacher. Second, we examine if this process of co-construction changes in the course of the VFCt (RQ2). We expect that after the intervention teachers used a stimulating teaching style, i.e., an increase in thought-provoking questions and encouragements. As a consequence students are frequently stimulated to use higher order thinking skills. We expect to find a pattern in which the reciprocal influence will take the form of optimal co-construction processes, i.e., more and longer student-teacher interactions on a more

stimulating and complex level. As teachers in the control condition did not participate in the intervention, no change was expected in their classroom interaction.

Third, if a difference is found between the classes in the intervention condition and control condition, we will examine the underlying pathways of change of all intervention classes (RQ3). The VFCt-intervention was meant as a perturbation to stimulate the system (student-teacher interactions) towards optimal co-construction, i.e., an active contribution of both partners. As teachers tried new instructional practices, we expected to see a period of temporal instability, i.e., destabilization, during the intervention period, as the system reorganizes.

2. Method

2.1 Participants

Twenty-three upper grade primary classes (grade 3-6, in the Dutch school system 'group 5-8') from the North of the Netherlands participated for three to four months in the school year 2013/2014 or 2014/2015. The teachers were recruited using flyers and personalized e-mails. The average age of the teachers in the intervention condition was 38 (range 23-54) with an average experience as a teacher of 13 years (range 1 – 32). The students' average age was 10.7 (range 8.4 – 13.2). The teachers in the control condition were comparable on the grades they taught (see table 1), on age ($M = 37$ years; range 24 – 54) and teaching experience ($M = 13$ years; range 1 – 30). The students' average age of the control condition was 10.6 (range 7.3 – 13.2). Teacher and parents of the participating students gave active consent before the start of the study. The study was approved by the Ethical Committee Psychology of the University of Groningen, The Netherlands.

2.2 Procedure

Teachers who participated in the intervention condition were offered the Video Feedback Coaching for teachers intervention (for more information see 5.1 Appendix A). Teachers in the intervention and control conditions are considered comparable in terms of motivation to participate

because the control condition was a waiting list condition and all teachers voluntarily participated in the intervention and control conditions.

The data of two intervention teachers were excluded for analyses because they did not participate in all video feedback coaching sessions (within a period of 6 weeks). One teacher from the control condition was excluded because only two out of four lessons were provided. This resulted in a total of 9 teachers who participated in the intervention, while the other 11 teachers were part of the control condition. The lessons were video recorded and these recordings were used as the primary source to evaluate the effectiveness of the intervention. Lesson content and instructional method was based on the teacher's own initiative, within 'earth and space' system — such as weather, air pressure, gravity, or the positions of the moon.

Each teacher in the intervention condition was observed during eight science and technology lessons, within a period of approximately three to four months. The first two lessons were pre-intervention lessons representing teaching-as-usual situations. Directly preceding the third lesson, the teacher received an introduction session about the aims of the professionalization trajectory. During this educational introduction, information about inquiry-based instruction strategies was provided and discussed. This included information about thought-provoking questioning styles, scaffolding, and inquiry-based learning activities, and video fragments of high-quality teacher-student interactions during science and technology activities. During the intervention-stage (lesson three to six), video feedback coaching was given immediately after every lesson. During each lesson, the coach (first author) selected several fragments to critically reflect upon, three of which were positive fragments and one fragment that showed (an example of) teacher behavior that could be improved. Teacher and coach discussed the video recordings of the lessons, making use of the teacher's personal learning goal. Attention was paid to the use of high-quality inquiry-based instruction strategies. Teachers gained insight into students' scientific understanding. In addition, they gained insight in their own role in the teaching-learning processes during science and technology education. The final two lessons were post intervention and were videotaped approximately two months (range 4 to 14 weeks) after the last video feedback coaching session.

Each teacher in the control condition taught two lessons at the beginning of the trajectory and two lessons approximately 2.5 months later (range 7 to 17 weeks). To assure teaching-as-usual conditions, teachers were free to choose whether or not they continued providing science and technology lessons between the premeasures and post measures.

2.3 Variables

Ten minutes of teacher and students' verbal interactions were captured by analysing the recorded science lessons. Four segments from the central section of each lesson were selected for coding: three minutes from the beginning, three minutes from the end, and two two-minute segments from the middle. The central section was defined as the part of the lesson where students were working and the teacher walked around to provide support. Coding started from the first task-related utterance. The two two-minute segments were moments in which a lot of teacher-student interaction took place, and the final three-minute segment took place before the teacher started classical lecturing. We coded all task-related student-teacher sequences. *Non-task related* sequences were excluded from further analysis. Teacher reactions were coded using an ordinal scale of 'level of stimulation' (based on the 'openness-scale' of Authors, 2013b; Oliveira, 2010). The scale ranged from 'giving instructions', 'providing information', 'asking a knowledge-based or closed question', 'posing encouragements', to 'posing a stimulating task-related follow-up or thought-provoking open question' (table 1a). 'Giving an instruction' is considered as least stimulating because it is considered to be associated with the smallest possible chance of co-constructing a high level of reasoning. 'Posing a task-related follow-up' is considered to be most thought-provoking and stimulating.

Task-related utterances of the students were divided in *complex* or *non-complex* utterances. *Non-complex* utterances were utterances related to the task at hand but did not display any understanding. For instance, the student reads out loud what he needs to do. *Complex* utterances were observations, predictions and explanations related to the task. Next, students' *complex* utterances were quantified based on a scale based on dynamic skill theory, using three tiers (table 1b; Fischer, 1980; Fischer & Bidell, 2006). This scale has proven useful for task-independent measures in the analysis of student's task-related utterances (Authors, 2012a; Rappolt-Schlichtmann et al., 2007; Authors, 2014).

Here, 1 means the least *complex utterances* on a sensorimotor level (e.g., expression of what they see), 2 refers to complex utterances on a representational level (e.g., expressions that go beyond simple action-perception couplings, but are still based on them), and 3 was scored when students expressed understanding about global laws and principles (e.g., abstract principles of thermodynamics can be applied to the situation at hand). The lowest possible level for 'explanations' was level 1, since an explanation contains at least a combination between what happened and a reason why this happened. The lowest possible level for 'predictions' was level 2, since a prediction requires at least a representation of the situation at hand. Coding was done with the aid of the software program 'Mediacoder 2009' (Authors, 2009). To establish the inter-observer reliability for the application of the coding scheme, the inter-observer agreement was determined by the first author and several independent coders for each codebook. The inter-observer agreement for teacher coding ranged from 70 to 87% and for student coding from 65 to 98%. The inter-observer reliability was considered substantial, with a Cohen's kappa of .71 for the teacher coding and .63 for the student coding (Viera & Garrett, 2005).

< Table 1 about here >

2.4 Data analysis

The data analysis of the first and second question was similar, in that the focus was on both conditions and on similar variables. State Space Grids (Hollenstein, 2013) were used to detect synchronized event sequences. This micro-genetic time-serial analysis was used to gain insight into dyadic characteristics of co-construction of each class at premeasure (RQ 1) and whether changes over time could be found (RQ 2). For data analysis the student-teacher interaction was taken as the unit of analysis. Hence, the focus was on each student utterances and the corresponding teacher reaction. In the SSG analyses, each grid consists of all possible states the student-teacher interaction can go to (see figure 2). For each moment in time the place of the student-teacher interaction is registered on the grid with a node. The successions of such nodes correspond with the trajectory of that student-teacher interaction, which, depending on the analysis, can concern the real-time timescale of one lesson or the

macro timescale of several lessons. Each node consists of a complexity level of the student (y-axis) and the extent to which the reaction of the teacher is stimulating (x-axis). The size of each node is an indication of the duration, relative to the total duration of that lesson, of that particular part of the interaction.

We illustrate this methodology in figure 2. The grid is divided into four quadrants. The quadrant in the lower left (Q1) represents no co-construction, a 'non-optimal' interaction pattern (students' utterances are non-complex; the teacher responses are non-stimulating). The quadrant in the upper right represents most desired co-construction (Q4), 'optimal' interaction patterns (students' utterances are complex; the teacher responses stimulating). The upper left and lower right quadrants (Q2 & Q3) represent 'suboptimal' interaction patterns and co-construction processes in which a mismatch occurs between teacher and student input (in Q2 students complex; teacher non-stimulating; in Q3 students non-complex; teacher stimulating). Figure 2 depicts the micro-level interactions of two classes during a single lesson. The left grid represents interaction which is mostly in the 'non-optimal' quadrant. Occasionally, the interaction shifts towards another cell, usually for a short time, represented by the fact that the nodes are small. The right grid shows mainly 'optimal' teacher-student interaction. Figure 3 depicts the macro-level pattern of these interactions (for a description how this pattern was established, see below).

< Figure 2 about here >

For answering RQ 1 and RQ 2, SSG's were made for each premeasure and post measure (micro level) per class. Next, the *preferred state* (a cell) was identified per lesson using the SSG measures 'total duration' and 'duration per cell'. The preferred state is operationalized as the cell in which most interaction occurs during that lesson, i.e., the cell with the longest duration. In order to map the macro level patterns, the next step was to create a new SSG using this information, resulting in one point (the most frequently visited cell / interaction pattern) per lesson (macro level). One point represents the interaction pattern of one lesson which was visited for the longest time (figure 3). In order to examine what form the co-construction processes took, we focused on which type of co-construction emerged for the longest period. We calculated the duration of time within each quadrant,

corrected for the number of cells within each quadrant, in order to study the *distribution of time* for certain types of interaction patterns during the lessons. Due to the size of the group and the fact that there were multiple dependent measures, a non-parametric test called Monte Carlo analysis (Todman & Dugard, 2001), was used that simulates the null hypothesis that the probability of finding a difference between premeasure and post measure or between conditions is based on chance alone. The random permutation was shuffled 10.000 times in order to calculate whether the empirically-found differences, e.g., the differences between intervention condition and control condition could be expected to occur on the basis of chance.

< Figure 3 about here >

For answering RQ3, we examined temporal instability, i.e., destabilization, of the system during the intervention lessons (lessons in between premeasure and post measure). One way to measure the (in) stability of the system is to document attractor states. A temporal absence of attractors implies increased variability in systems behavior. Several methods can be used to identify attractors (Hollenstein, 2013). We used the selection of the cell(s) with the highest mean duration of visits and the highest number of events per lesson (e.g., Pennings et al., 2014), as an indicator of an attractor state. We operationalized 'highest' as the duration and the number of events should exceed the chance at least two times of being in a cell. Grid measures, i.e., 'duration per cell', 'overall duration per lesson' and 'number of events', were used to determine whether the preferred states of interaction of each lesson could be labeled as *attractors*.

3. Results

3.1 Co-construction of scientific understanding during regular lessons (RQ 1)

During the premeasures, for 18 out of 20 classes, the preferred state of interaction was in the 'non-optimal' interaction quadrant (Q1; see figure 4). Fragment 1 describes an interaction showing how this was seen during the activity. Here, the teacher starts the interaction with a knowledge-based question, self-iterating the answer. The student formulates which color the moisture has and the

teacher continues providing a possible explanation about why the experiment did not turn out as she expected. This fragment illustrates that the teacher is actively providing information while at the same time limiting the opportunities for the student to construct this insight. Appendix B shows that during lessons one and two (of all classes) attractors only appeared in cell 1/1 ('instruction' / 'non-complex'), 2/1 ('information' / 'non-complex') and 3/1 ('closed' / 'non-complex'), this means that most interactions at premeasure were strongly drawn toward 'non-optimal' interaction, indicating no co-construction.

The distribution of time within each quadrant was distributed equally in both conditions, in that most time was spent in Q1, followed by Q3. The least time was spent in Q2 and Q4 (see table 2). The control condition spent more time in Q1 compared to the intervention condition than could be expected on the basis of chance (Q1: Intervention = 55%, Control = 67%, $p = .04$; Q2: Intervention = 11%, Control = 6%, $p = .19$; Q3: Intervention = 24%, Control = 21%, $p = .34$; Q4: Intervention = 11%, Control = 6%, $p = .20$).

< Figure 4 about here >

< Fragment 1 about here >

3.2 Change under influence of the intervention (RQ 2)

For the intervention condition, different patterns of co-constructing scientific understanding were found at post measure compared to premeasure. As figure 5 shows, some teacher-student interaction patterns now took place in the 'optimal' interaction quadrant (Q4), indicating more optimal co-construction. 50% of the *preferred states* were now in the 'suboptimal' or 'optimal' quadrant. Fragment 2 is an illustration of how students co-construct scientific understanding together with the teacher during an inquiry-based learning situation.

The *distribution of time* within each quadrant changed from premeasure to post measure (table 2). The difference between premeasure and post measure, concerning the proportion of time spend in Q1 (Pre = 55%, Post = 41%, $p < .01$) and Q4 (Pre = 11%, Post = 16%, $p = .10$) was larger than was

expected on the basis of chance alone (Q2: Pre = 11%, Post = 13%, $p = .28$; Q3: Pre = 24%, Post = 30%, $p = .18$). This indicates that a substantial part of the interaction has shifted away of 'non-optimal' interaction patterns towards 'optimal' interaction patterns, indicating optimal co-construction.

For the control condition, no differences were found in the preferred states of interaction. 'Non-optimal' interaction patterns were the *preferred state* of all classes, except 2 (5.2 appendix B). The *distribution of time* within each quadrant did not change from premeasure to post measure (table 2; Q1: Pre = 67%, Post = 64%, $p = .33$; Q2: Pre = 6%, Post = 9%, $p = .32$; Q3: Pre = 21%, Post = 20%, $p = .48$; Q4: Pre = 6%, Post = 7%, $p = .42$).

< Table 2 about here >

< Figure 5 about here >

< Fragment 2 about here >

3.3 Variability in the interactions (RQ 3)

Appendix B lists that *attractor* states were detected in individual pathways of classes in the co-construction of scientific understanding (5.2 appendix B). However, individual differences were pronounced. Some classes stabilized into one attractor state per lesson, in other classes multiple attractors were found within a lesson, while in other classes no attractors could be found at all. Over time similar individual differences were found. Interactions of class 1 and 7 showed expected pathways; i.e., they emerged in a 'non-optimal' attractor during premeasures, followed by 1 or 2 lessons without attractors, followed by interactions emerging in 'optimal' attractors (5.2 appendix B). The other classes show non-expected trajectories, in different forms. For example, in class 2 and 4 partly expected trajectory in that there appeared to be a temporal instability of the system, i.e., no attractor for three lessons, followed by stabilization into an attractor, in the consecutive lessons. However, this did not result into an attractor in the 'optimal' quadrant. In class 5 and 8 attractors were found during all intervention lessons. However, the data suggests that during post measure the system became instable, in that student-teacher interactions did not emerge into an attractor. This indicates partly expected trajectories, in that was found, late in the intervention. It is therefore not clear whether

the system was capable of stabilizing into a more preferred state. Class 3 and 9 were also quite variable, in micro behavior, during the lessons, only stabilizing into an attractor in one or two lessons. This indicates unexpected trajectories. Class 6's attractor emerged and remained in the 'non-optimal' quadrant until a sudden jump. After the jump, the student-teacher interaction changed into an attractor in the 'optimal' quadrant. This indicates an unexpected trajectory, as no sign of destabilization was found. However, in terms of change towards an 'optimal' interaction pattern, this class seems to indicate a rather ideal trajectory.

4. Conclusion and discussion

The present study was employed using a complex dynamic systems perspective in order to examine the effect of the Video Feedback Coaching for teachers on the process of co-constructing scientific understanding. The first question focused on the co-construction of scientific understanding during naturalistic science and technology lessons, in examining the alignment between students' complexity level of scientific understanding and the extent to which teacher utterances were stimulating. The results from the premeasures showed that in all classes, the *preferred state* of interaction could be considered as 'non-optimal' interaction patterns that recurs over time. This suggests that in a naturalistic science and technology lesson scientific understanding rarely takes the form of teacher utterances that evoke students' scientific understanding.

The results also showed that the participants in the intervention condition changed their interaction style whereas the participants in the control condition did not (hypothesis accepted). The *preferred state* of interaction of several classes changed to 'optimal' co-construction. This means that the students' expression of scientific understanding evoked high-quality teacher questions and utterances and these in turn evoked more scientific understanding. This suggests that the intervention had an effect on the teacher, the student as well as on the alignment between the partners.

The final question examined underlying characteristics of change in the co-construction of scientific understanding. The use of SSG enabled us to analyze destabilization as indicator of change (*attractors*). The results showed that in some classes

temporal destabilization was found (hypothesis 3 partly accepted). However, the type of instability showed differences between classes. Three classes (1, 6, and 7) were able to transform the coaching into the expected change trajectory from 'non-optimal' interaction patterns towards 'optimal' co-construction processes. Interestingly, these three classes showed different underlying pathways that could explain these change over time. For class 1 the instability of the system was found in the temporal absence of attractors during one or more lessons during the intervention period. However, for class 6 no indications of destabilization were found during the intervention trajectory. These findings highlight the nonlinear nature of change and the importance of studying inter-individual differences, even in case the intervention was effective (Lichtwarck-Aschoff, Hasselman, Cox, Pepler, & Granic, 2012; Authors, 2011a).

4.1 Concluding remarks

The data suggested that the implementation of the intervention did not result into optimal teaching-learning processes in all classes. We argue that the intervention is a perturbation in the sense that it is actively changing existing practices. Such perturbations result in the potential breakdown of various established patterns, such as the way in which the teacher keeps order in the class. Classroom order is most likely a necessary condition for learning to occur (Brekelmans, Wubbels & Tartwijk, 2005). It seems likely that keeping order may be more difficult by changing practices, resulting in fewer opportunities to focus on the co-construction of scientific understanding. Given that we disturbed existing routines in the intervention condition, it is possible that teachers and students in some classes had to cope with too many changes at the same time. However, this might especially be the case for those classes in which the rules are not clear/set yet. In this study, this might be especially the case for two intervention classes (classroom 3 and 9). These classes did rarely stabilize into an attractor. The resemblance between these teachers was that they just started teaching in the particular classroom. One teacher was a freshman, while the other had just returned from a maternity leave of a few months. The 'inexperience' of the teacher, in the sense of being 'inexperienced' for this particular classroom, might indicate that the system did not have had enough time to establish stable teaching-learning interaction patterns. It might be that at first a lot of time goes to classroom order and familiarizing to each other's learning and teaching needs. Put differently, 'optimal' co-construction

can only emerge when students and teachers both can display high quality utterances, which implies that there should be opportunities to do so. Further research should provide insight into whether teacher-experience is an explaining factor for the effectiveness of the intervention.

Several studies have shown that high quality instruction strategies of teachers can result in cognitive gains of students (e.g., Baumert et al., 2010; Lee & Kinzie, 2012; Authors, 2013b; Oliveira, 2010; Authors, 2014). This study showed that students' scientific understanding is triggered when teachers ask and don't tell. Previous research often examined the effect of questioning strategies in a unidirectional way (from teacher to student), specifying the eventual effect as a difference between pretest and posttest performance, without focusing on underlying dynamics. Our study adds to and elaborates on these studies in several ways. First, the pretest and posttest performance used in this study are based on micro-genetic measures of the co-construction of meaning. This means that the bidirectional relation of the interactions is taken into account. Second, the intervention lessons are used as an important source of insight into the dynamics of change in learning-teaching processes.

The results of this study underlines that learning takes the form of a nonlinear process. The notion that the system changes due to a temporal instability of the system can be used to strengthen intervention studies. For instance, this temporal instability of the system might be displayed as a temporal drawback in micro-level behavior (as is known from therapy; Lichtwarck-Aschoff et al., 2012). However, this study shows that the system is able to self-organize again towards more preferred states. For practitioners or coaches, this temporal instability should be interpreted as a step forward in order to change, instead of a step backwards. For teachers this finding might strengthen their belief that their attempt to change is in fact effective, even when they experience destabilization or initial resistance.

Taken together, we showed that processes of co-constructing scientific understanding can entail long-term changes in existing, self-sustaining states between the teacher and students, as measured in real-time science and technology lessons. The use of the state space grid technique allowed studying differences in student-teacher interaction by means of quantitative indicators. In

terms of effectiveness of the intervention, we conclude that from a micro-level dynamic perspective the implementation of the intervention is effective.

4. 2 Limitations and future research

The intensive time serial data collection, as employed in this study, has its strength, in that it is basically the only way to gain insight into the actual processes of teaching and learning, but it also has limitations. The small sample implies that generalization of findings towards the population of teachers is difficult. However, the aim of this study was to gain insight in underlying processes of change. The fundamental dynamic characteristics of change, i.e., the formation and occurrence of attractors and patterns of temporal instability during an intervention, provide a generalized framework for other intervention studies.

The period until the post measure varied considerably between classes. The period between the intervention period and post measures was intended as a period for teachers to be able to work independently with the newly acquired skills, without external perturbation from a coach. On that basis we consider the periods comparable because we reasoned that a few weeks are probably sufficient to enable students and teachers to incorporate the newly learned skills into their habitual practices. However, we do acknowledge that a more equal period until post measure was more desirable in terms of making valid comparisons.

The current study primarily focused on the characteristics of change during the intervention. However, this was not examined for the control condition, as there were no measures in between the premeasure and post measure videotaped. The essence of the control condition was that there was no particular intended and obligatory between-measures activity, which reflects a teaching-as-usual situation. In the intervention condition, an explicit perturbation of the system was considered as a reason to study the between-measures micro dynamics. Although the intra-individual differences provide insight into how the intervention works on the micro level, it would be interesting to examine whether these characteristics of change cannot be found in a control condition. The recommendation is therefore to replicate this study, this time with an extra control condition. Hence, a more ideal setup consists of an intervention condition where a perturbation is applied in the form of an intervention, a

control condition which is teaching as usual, and a second control condition in which the number of between measurement science lessons is the same as the intervention condition. This would provide opportunities to study inter-individual differences in student-teacher interactions.

In this study we termed student-teacher behaviors as 'non-optimal', 'suboptimal' or 'optimal' ways of co-construction. However, as studies focusing on scaffolding behavior show (Van de Pol et al., 2010), there exist no single predetermined way for stimulating the use of higher order thinking skills in all students. A limitation of this study might therefore be that the reaction of the teacher was not coded on contingency (Van de Pol et al., 2011). That is, it was not coded whether the teacher's support was adapted to the current level of functioning of the students. Given the current level of functioning of the students, the teacher should determine which reaction is likely to support students to proceed to a higher level of functioning. This means that what is termed 'non-optimal' on the basis of general attractor properties is in fact 'optimal' in some specific classes. For instance, if a student is not capable of answering the question 'How would you explain this?' it might be the case that the question is out of the students 'zone of proximal development' (Vygotsky, 1986). This means that the teacher should adapt the next response towards the current level of the student (Authors, 2012b). After considering what the current level of the student is, a closed question or providing some information might cue the student into the direction of formulating an explanation. A recommendation for future study is therefore to focus on the contingency of teacher behavior on students' cognitive behavior (Van de Pol et al., 2011).

4.3 Practical implications

A recommendation for educational practitioners is to expand the intervention in two ways. First, the results showed that most classes showed destabilization during the intervention period and some during the post measures. In addition, some classes stabilized at the end of the intervention and this was sustained during the post measures. The introduction of inter-colleague inter-vision or coaching (Bruining, Loeffen, Uytendaal, & De Koning, 2012), that help sustain the presence of high quality co-constructive teaching is therefore advised. The sustainability of particular attractors is

considered to be linked to the entire structure of relationships between components of a particular school.

Second, some classes showed changes, but these changes did not emerge in stable attractors at post measure. If a system has not yet stabilized into a new attractor, it seems likely that the system will be drawn back to the previously stable state. It might be that the intervention period was too short to yield sustained, stable changes. Several studies show that longer periods of intervention seem necessary to yield sustained behavioral change (e.g., Loucks-Horsley, 1996). Another consideration for future research is therefore to increase the idiosyncratic nature of the intervention and to prolong the intervention period if the system did not yet stabilize into a desired state. This can be done by closely monitoring the change processes of each system.

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